(12) UK Patent Application (19) GB (11) 2 329 476 (13) A

(43) Date of A Publication 24.03.1999

(21) Application No 9819190.1

(22) Date of Filing 04.09.1998

(30) Priority Data
(31) 9718957 (32) 08.09.1997 (33) GB

(71) Applicant(s)
University of Manchester Institute of Science and Technology
(Incorporated in the United Kingdom)
P O Box 88, Sackville Street, MANCHESTER, M60 1QD, United Kingdom

(72) Inventor(s)
Wu Qiang Yang

(74) Agent and/or Address for Service
Marks & Clerk
Sussex House, 83-85 Mosley Street, MANCHESTER, M2 3LG, United Kingdom

(51) INT CL^6
G01F 1/74, G01N 27/22

(52) UK CL (Edition Q)
G1N NCCE NCVX N19B2B N19F7B

(56) Documents Cited
GB 2223850 A GB 2214640 A

(58) Field of Search
UK CL (Edition Q) G1N NCCA NCCE NCCJ NCCX NCVX
INT CL^6 G01F, G01N
Online: WPI

(54) Abstract Title

Image creation in a tomography system

(57) A method and apparatus for iteratively creating an image representing internal properties of a region from measurements of electrical parameters such as capacitance at the perimeter of the region. Initial image data is calculated from the measurements to represent an initial estimation of the properties of the region. Estimated parameter measurement data is then calculated representing the measurements which would be expected if the initial estimation of the properties was accurate. The difference between the parameter measurements and the estimated parameter measurement data is calculated, and image correction data is calculated from the calculated difference data as if the calculated difference data had been measured at the perimeter of the region. The initial image data is combined with the image correction data to define interim image data and the process is repeated with the interim image data substituted for the initial image data to produce final image data.

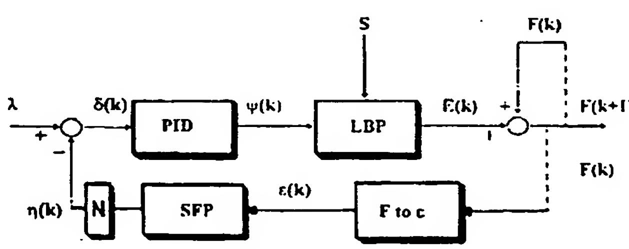

FIG. 3

GB 2 329 476 A

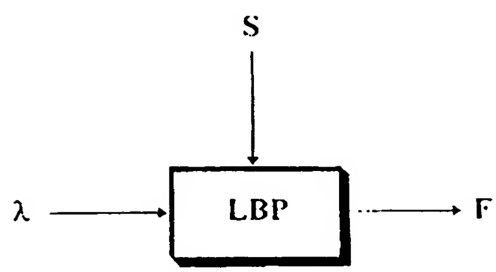

FIG. 1

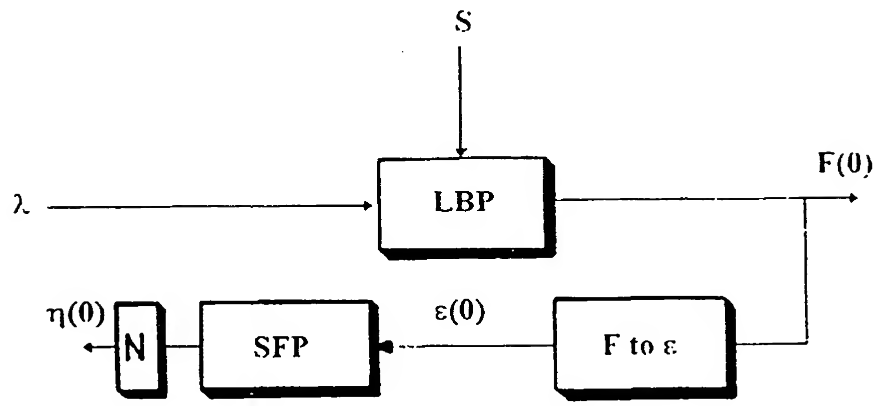

FIG. 2

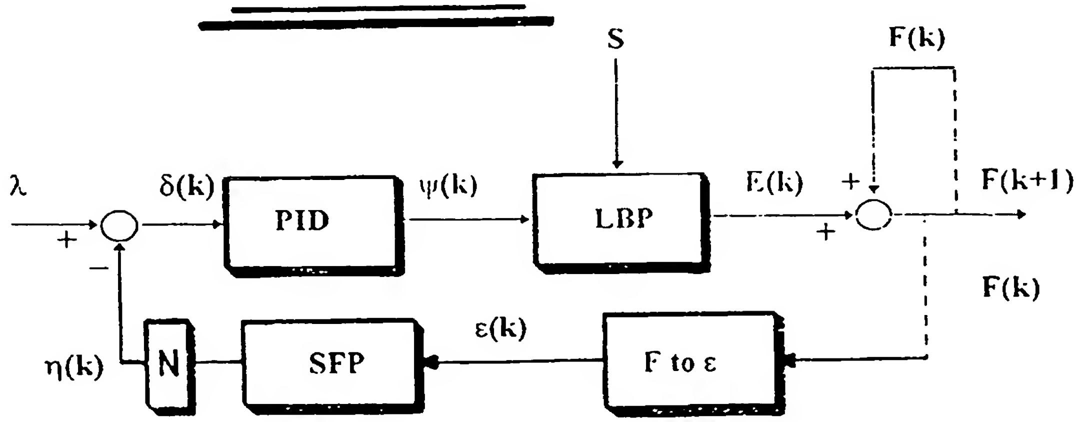

FIG. 3

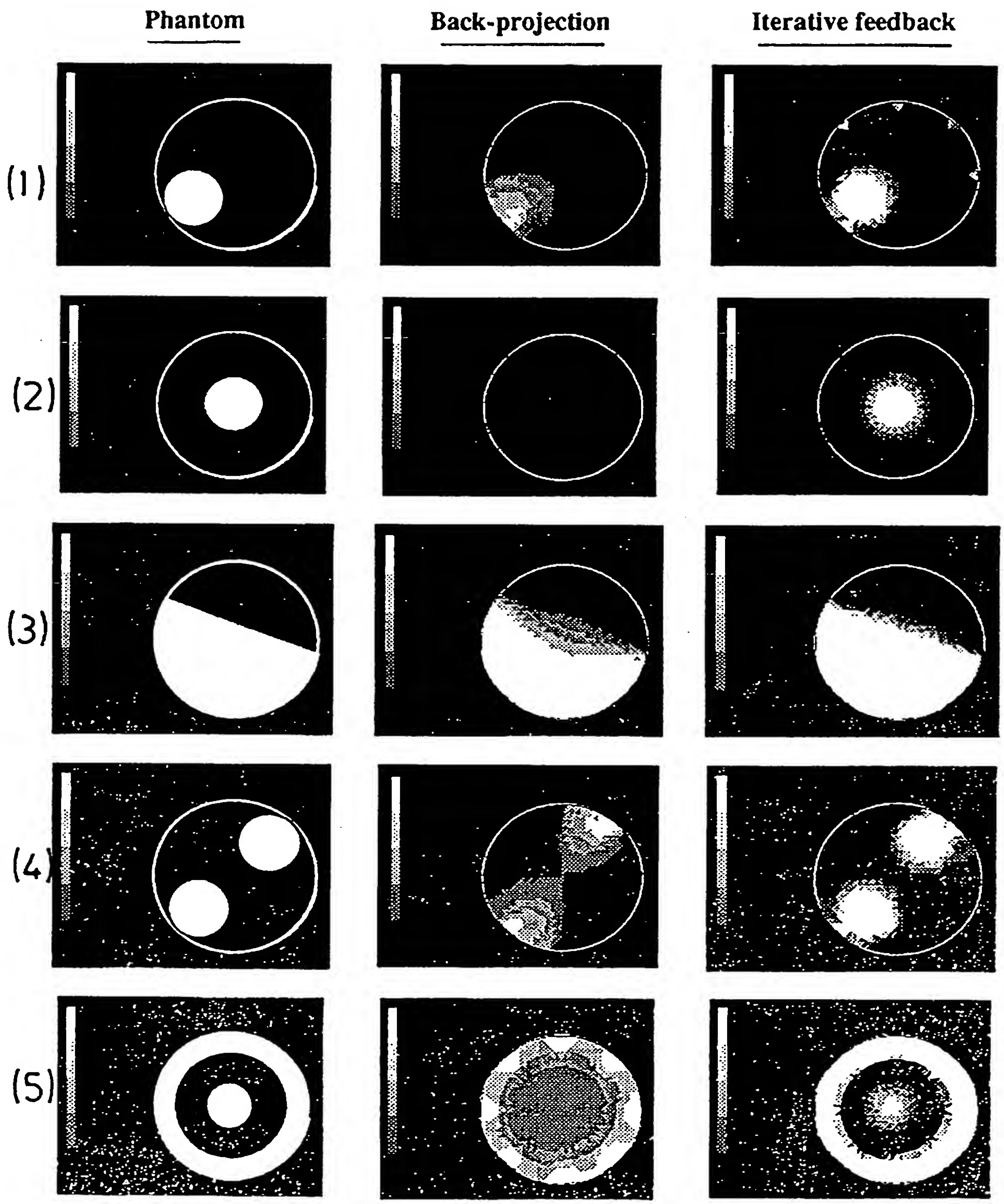

FIG. 4

IMAGE CREATION

This invention relates to image creation, and particularly but not exclusively to a method and apparatus for creating an image from data obtained using electrical capacitance tomography

The aim of electrical capacitance tomography (ECT) is to produce an image of a cross-section of a conduit surrounding dielectric materials of different relative permittivities [W.Q. Yang, M.S. Beck and M. Byars, Electrical capacitance tomography -- from design to applications, *Measurement + Control,* **28 (9)**, 1995, pp 261-266]. A series of measurements of capacitance across a conduit is obtained by exciting electrodes positioned around an outer wall of the conduit. The capacitance measurements are used to construct an image of a section through the conduit which represents the relative proportions and location of dielectric materials within the conduit.

Conventional ECT systems employ a linear back-projection (LBP) algorithm to reconstruct images from ECT data. The effect of permittivity changes at an array of points on a section through a conduit is measured for each pair of single electrodes, and a capacitance sensitivity distribution, known as a sensitivity map, is produced. Once the sensitivity map is known, an image of the permittivity of dielectric materials within that section of the conduit may be obtained by linearly superimposing the sensitivity maps, using capacitance measurements for each single-electrode pair as weighting factors [C.G. Xie, S.M. Huang, B.S. Hoyle, R. Thorn, C. Lenn, D. Snowden and M.S. Beck, Electrical capacitance tomography for flow imaging: system model for development of image reconstruction algorithms and design of primary sensors, *IEE Proc.-G*, **139 (1)**, 1992, pp 89-97]. The LBP algorithm is simple and fast, but is essentially a qualitative algorithm and produces low quality images.

It is known that to create an image from ECT data using an iterative algorithm, an image is formed using measured capacitance values, estimations of capacitance values which would be expected given a distribution as represented by the image are compared with the measured values, and a new image is then constructed which reduces the difference between the estimated and measured values. The process is repeated until the difference is below a predetermined tolerance. Various strategies for optimising the iterative process have been developed [Ø. Isaksen, A review of reconstruction techniques for capacitance tomography, *Measurement Science and Technology*, 7 (3), 1996, pp 325-337; Q. Chen B.S. Hoyle and H.J. Strangeways, Electric field interaction and an enhanced reconstruction algorithm in capacitance process tomography, in *Tomographic techniques for process design and operation*, edited by M.S. Beck, E. Campogrande, M. Morris, R.A. Williams and R.C. Waterfall, Computational Mechanics Publications, Southampton and Boston, 1993, pp 205-212]. A finite element method is usually used to calculate capacitance values from the image, a technique known as "solving the forward problem". Iterative image reconstruction produces images which are superior in quality to those produced using linear back-projection algorithms. However, known methods of iteration are time-consuming, and iterative algorithms are consequently limited mostly to off-line analysis.

It is an object of the present invention to provide a method and apparatus for image creation which obviates or mitigates the above disadvantage.

According to the invention there is provided a method for creating an image representing internal properties of a region from measurements of electrical parameters at the perimeter of the region, wherein initial image data is calculated from the measurements to represent an initial estimation of the properties of the region, estimated parameter measurement data is calculated representing the measurements which would be expected if the initial estimation of the properties was accurate, the difference between the parameter measurements and the estimated parameter

measurement data is calculated, image correction data is calculated from the calculated difference data as if the calculated difference data had been measured at the perimeter of the region, the initial image data is combined with the image correction data to define interim image data, and the process is repeated with the interim image data substituted for the initial image data to produce final image data.

The method may be performed by a process wherein in a first step electrical parameters are measured at the perimeter of the region to define a first data set, the measured electrical parameters being a function of the internal properties, in a second step a second data set is calculated defining an image representing an estimation of the internal properties which resulted in the measured parameters, in a third step a third data set is calculated representing the parameter measurements at the perimeter of the object that would be detected if the second data set accurately represented the internal properties, in a fourth step a fourth data set is calculated representing the difference between the first and third data sets, in a fifth step a fifth data set is calculated defining an image representing an estimation of the internal properties which if present would result in parameter measurements represented by the fourth data set, in a sixth step the second and fifth data sets are combined to define a sixth data set defining a revised image representing a revised estimation of the internal properties which resulted in the measurement parameters, and in a seventh step the second data set is replaced by the sixth data set to provide a new second data set, the third to seventh steps being repeated to produce data sets representing successively revised image representations until the difference between a calculated data set representing parameter measurements and the first data set has been reduced in a predetermined manner.

Thus the invention relies upon the concept of using feedback information in the form of images representing the difference between actual and estimated measurements to create revised image data.

Preferably, the third data set is normalised using data sets calculated for low and high permittivity values.

Preferably, the third to seventh steps are repeated until an average of the difference-representing data sets is less than a predetermined value, the average most preferably being a root mean square average.

Preferably, the second and fifth data sets are formed using a linear back projection algorithm. The data so formed are limited to thresholds corresponding to maximum and minimum values of the measured parameter.

Preferably, the data sets representing data set differences are modified by a controller prior to the subsequent image defining data set calculation, the controller acting to minimise the number of iterations required to reduce the average of the difference-representing data sets to a predetermined value.

Preferably, the controller acts to prevent the average of the difference-representing data sets from diverging away from a predetermined value, the average most preferably being a root mean square average.

Preferably, elements of the sixth set are modified to fall within predetermined limits. A set of permittivity values may be calculated from the modified sixth data set.

Preferably, the electrical parameters measured at the perimeter of the region are voltages which are determined by capacitances defined between an array of electrodes positioned around the region.

Preferably, the region is defined by the interior of a conduit surrounding a mixture of two or more materials of differing permittivities.

The present invention also provides an apparatus for creating an image representing internal properties of a region from measurements of electrical parameters at the perimeter of the region, comprising means for calculating initial image data from the measurements to represent an initial estimation of the properties of the region, means for calculating estimated parameter measurement data representing the measurements which would be expected if the initial estimation of the properties was accurate, means for calculating the differences between the parameter measurements and the estimated parameter measurement data, means for calculating image correction data from the calculated difference data as if the calculated difference data had been measured at the perimeter of the region, means for combining the initial image data with the image correction data to define interim image data, and means for substituting the interim image data for the initial image data for further processing.

A specific embodiment of the invention will now be described by way of example with reference to the accompanying drawings, in which

Figure 1 is a schematic illustration of an algorithm used in accordance with the invention;

Figure 2 is a schematic illustration of an initial process used in an image creation method according to the invention;

Figure 3 a schematic illustration of an iteration process used in an image creation method according to the invention; and

Figure 4 reproduces a series of images which illustrate results obtained in accordance with the invention.

An image of a cross-section of a conduit surrounding dielectric materials of different relative permittivities is obtained using an electrical capacitance tomography sensor array distributed around a section of the conduit. The sensor array comprises a

series of electrodes which provide measurements of capacitance between different pairs of electrodes across the section of the conduit. The capacitance measurements are used to create an image using a technique known as Linear Back Projection (LBP).

The LBP algorithm for a mixture of a low permittivity material and a high permittivity material is expressed by the following equations:

$$F(p) = \frac{\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \lambda_{ij} S_{ij}(p)}{\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} S_{ij}(p)} \tag{1}$$

$$\lambda_{ij} = \frac{C_{ij}^{m} - C_{ij}^{l}}{C_{ij}^{h} - C_{ij}^{l}} \tag{2}$$

where N is the number of measurement electrodes comprising the sensor array,
F(p) is the fraction of high permittivity material present at a position p within the cross-section of the conduit,
$S_{ij}(p)$ is the sensitivity of a pair of electrodes to a change of permittivity at a position p within the cross-section of the conduit,
C_{ij}^{l} is the capacitance between a pair of electrodes when the conduit is filled with low permittivity material,
C_{ij}^{h} is the capacitance between a pair of electrodes when the conduit is filled with high permittivity material,
C_{ij}^{m} is the capacitance between a pair of electrodes during measurement, and
λ_{ij} is the normalised change in capacitance.

The variable $S_{ij}(p)$ is determined for each position p within the conduit by measuring the effect of permittivity changes for each pair of electrodes. The resulting set of values is commonly referred to as a sensitivity map, a separate map being produced for each pair of electrodes. The LBP algorithm produces an image of a

section through the conduit by linearly superimposing the sensitivity maps for each electrode pair using capacitance measurements as weighting factors

An LBP image reconstruction algorithm is shown schematically in Fig. 1, where λ represents a set of normalised capacitance changes measured from the electrodes, S is the set of sensitivity maps, and F is an image which represents a normalised permittivity distribution. The LBP reconstruction algorithm can be considered as a multi-variable open loop system.

Although the LBP algorithm is unable to produce an accurate quantitative image, it does provide a useful qualitative image. The present embodiment of the invention uses an image reconstructed by the LBP algorithm to provide an initial set of values for a subsequent iteration process. Since the LBP algorithm is not an accurate mathematical expression relating the measured capacitance values and the image, the image reconstructed by the LBP algorithm must differ, to some extent, from the actual permittivity distribution. Consequently normalised capacitance changes calculated from the reconstructed image assuming that the image accurately represents the distribution will differ from the capacitance changes measured from the sensor. These differences between the measured and calculated capacitance values are used as inputs for the iteration process.

Figure 2 illustrates the process of obtaining an initial set of difference values, where the designations used for Figure 1 retain their meaning, and

F to ε represents a conversion of the image obtained by LBP into a permittivity distribution,

$\varepsilon(0)$ represents the resulting permittivity distribution,

SFP represents conversion of the permittivity distribution into a set of calculated capacitance values (known as Solving the Forward Problem), and

$\eta(0)$ represents the capacitance calculated from the conversion.

The image obtained by LBP is converted to the permittivity distribution using linear interpolation according to the following equation:

$$\varepsilon(p) = \begin{cases} \varepsilon_l & (F(p) \leq 0) \\ \varepsilon_l + F(p)(\varepsilon_h - \varepsilon_l). & (0<F(p)<1) \\ \varepsilon_h & (F(p) \geq 1) \end{cases} \qquad (3)$$

where ε_l and ε_h are low and high permittivity values respectively.

In principle, all the permittivity values, $\varepsilon(p)$, should be between ε_l and ε_h. However, due to an effect known as the 'soft-field effect', the image values F(p) may be greater than '1' or less than '0' for some pixels, which will result in permittivity values being larger than ε_h or smaller than ε_l if they are calculated by simply interpolating from F(p). Two thresholds are therefore used to limit $\varepsilon(p)$, as shown in Equation (3) so that it is always between ε_l and ε_h.

The new iterative image creation method of the invention may be implemented using the techniques illustrated in Figure 3, where the designations used for Figures 1 and 2 retain their meaning, and

$\eta(k)$ represents the set of normalised capacitances calculated by solving the forward problem,
$\delta(k)$ represents the differences between the measured capacitances and the calculated capacitances,
PID represents control regulation techniques used to optimise the iteration,
$\Psi(k)$ represents the regulated difference values between the measured capacitances and the calculated capacitances,
E(k) represents an error image reconstructed from the difference values using the LBP algorithm
F(k), F(k+1) are the current and subsequent revised images

$\varepsilon(k)$ is the permittivity distribution

The set of capacitances which are calculated from the estimated image by solving the forward problem are normalised before being subtracted from the (normalised) set of measured capacitances. To do this, all of the pixels comprising the image are set to the lowest possible permittivity value and then to the highest possible permittivity value, and the finite element software (ie. the forward problem solver) is used to calculate maximum and minimum capacitance values respectively. The set of capacitances calculated from the estimated image are normalised in relation to the calculated maximum and minimum capacitance values.

Since the measured capacitance values and the estimated capacitance values are both normalised, the subtraction of the estimated capacitances from the measured capacitances is essentially a comparison of capacitance data patterns, rather than a comparison of absolute values. This approach enables effective comparison between the two sets of data, which is unhindered by the inaccuracy of finite element solutions.

At a k^{th} iteration, a set of normalised capacitances, $\eta(k)$, is calculated from the estimated permittivity distribution, $\varepsilon(k)$, by solving the forward problem (SFP). The calculated set of normalised capacitances $\eta(k)$ is subtracted from the measured set of normalised capacitances λ. The set of differences, $\delta(k)$, between the measured and calculated capacitance values is regulated by a controller (PID) whose output $\Psi(k)$, is used, via the LBP algorithm, to reconstruct a "difference" image, E(k), by means of the sensitivity maps, S.

$$E(p) = \frac{\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \Psi_{ij} S_{ij}(p)}{\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} S_{ij}(p)} \tag{4}$$

The difference image E(k) represents, to some qualitatively trustworthy extent, the difference between the current image and the true image. It is added to the current image, F(k), to obtain a new image, F(k+1). The process is repeated until the root mean square (RMS) value of the difference values reaches a defined low value.

$$e_{\mathrm{RMS}} = \sqrt{\frac{\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(\lambda_{ij} - \eta_{ij}\right)^2}{N(N-1)/2}} \qquad (5)$$

Comparing Fig. 1 and Fig 3, it is evident that the conventional LBP algorithm is an open loop system whilst the new iterative algorithm is a closed loop system. The system of Fig. 3 has the same structure as a sampled-data multi-variable process control system with N(N-1)/2 inputs (the number of capacitance measurements). The number of outputs corresponds to the number of pixels forming the imaging area (normally a few hundred pixels). By means of the sensitivity maps and the LBP algorithm a large number of outputs are controlled by a small number of inputs. The controller may use process control techniques, such as a PID (proportional, integral and differential) controller, as shown in Figure 3, to optimise the system performance. Equation 6 shows one such process control technique:

$$\Psi_{ij}(k) = P\delta_{ij}(k) + I\sum_{m=0}^{k}\delta_{ij}(m) + D[\delta_{ij}(k) - \delta_{ij}(k-1)] \qquad (6)$$

where, P represents a proportional parameter used to control the speed of the "transient process" and ensure system stability

I represents the integration parameter used to eliminate the "static error" (δ in Fig. 3)

D represents the differential parameter used to speed up the initial process.

The aims of using a PID control are to shorten the transient process and to ensure a stable system that will settle with zero error. Since this algorithm is based on

iterative principles and feedback control concepts, it may be called an iterative feedback algorithm. In a typical arrangement of PID control, I is initially set to zero so that the P and D functions act to speed up the initial process. After a predetermined number of iterations D is set to zero, and the P and I functions act to ensure that the system remains stable and to eliminate the static error (δ in Fig. 3).

The effectiveness of the present embodiment of the invention has been investigated by experiments carried out using an 8-electrode sensor of 84 mm diameter and an AC-based ECT system [W.Q. Yang, Key features of a newly designed capacitance tomography system, *Proc. of 8th Int. Conf. of Flow Measurement,* 20-24 Oct. 1996, Beijing, China, (edited by B. Zhang, L. Ham and X Zhao, published by Standard Press of China, 1996), pp 480-485]. The measurement electrodes of 10 cm in length were symmetrically mounted outside of a section of insulating pipe. The ECT system was calibrated with air (ε_r = 1.0) as the low permittivity material and polystyrene beads (effectively ε_r = 1.8) as the high permittivity material. Different object distributions were tested, including

(1) a single circular object of 32 mm in diameter which was positioned near the sensor wall
(2) the same circular object positioned in the centre which is the least sensitive area
(3) stratified distribution
(4) two circular objects
(5) a high permittivity ring and a circular object of 26 mm in diameter in the centre.

In each case, 28 normalised capacitances were taken from the ECT system and used to reconstruct an image. Note that for an N-electrode system, there are N(N-1)/2 independent electrode pair capacitance measurements. The images reconstructed using the iterative feedback algorithm with 10 iterations are shown in Figure 4. For comparison purposes, the real distributions and the images reconstructed using the

LBP algorithm (which were used as the initial image for the subsequent iterations) are also shown.

The experimental results show that:

(1) When an object is positioned near the sensor wall, the invention produces a better image than the LBP algorithm in shape.

(2) When the object is moved to the centre of the imaging area, it almost disappears when the LBP algorithm is used, while the invention produces an equally good image as when it is positioned near the wall.

(3) For the stratified distribution, the LBP algorithm produces an image with blurred boundary, i.e. a large transient zone. The invention, however, produces an image with a clear boundary.

(4) With two objects near the wall the image reconstructed by the LBP algorithm is distorted and the two objects are "connected" together. In contrast, the invention produces an image with good separation and correct shapes.

(5) Due to the so-called "shielding effect", the LBP algorithm completely fails to reconstruct a correct image for the distribution of a ring plus an object in the centre. Using the invention, however, the central object can still be seen clearly.

The results demonstrate that the invention can produce images of better quality than those produced by the LBP algorithm. The images reconstructed using the invention are much closer to the real object(s), both in size and in position, than those reconstructed by the LBP algorithm. The experiments also showed that as the number of iterations increased, the RMS capacitance error, e_{RMS}, defined by equation (5), decreased significantly, typically 10 times by 10 iterations. This confirms that the iterative processes converge. In control terminology, the feedback system is stable.

The invention is based on an iterative principle and control system design concepts. The iterative process can be treated as a sampled-data process control system and the controller parameters can be chosen by classic control system design techniques to reduce the settling time of the system and ensure that the iterative process converges. This method does not require prior knowledge of object(s) distribution in contrast to some known iterative algorithms for ECT which require explicit object models (e.g. one needs to know, in advance, a single circular object, two circular objects or stratified distribution), which may be difficult to obtain [Ø. Isaksen, reference given above].

The invention may also be extended to other tomographic imaging systems, e.g. electrical resistance tomography (ERT) and electro-magnetic tomography (EMT).

The iterative feedback algorithm has been implemented in C. It runs quickly, less than one second per iteration with a Pentium computer, since it does not require intensive computation.

CLAIMS

1. A method for creating an image representing internal properties of a region from measurements of electrical parameters at the perimeter of the region, wherein initial image data is calculated from the measurements to represent an initial estimation of the properties of the region, estimated parameter measurement data is calculated representing the measurements which would be expected if the initial estimation of the properties was accurate, the difference between the parameter measurements and the estimated parameter measurement data is calculated, image correction data is calculated from the calculated difference data as if the calculated difference data had been measured at the perimeter of the region, the initial image data is combined with the image correction data to define interim image data, and the process is repeated with the interim image data substituted for the initial image data to produce final image data.

2. A method according to claim 1, wherein in a first step electrical parameters are measured at the perimeter of the region to define a first data set, the measured electrical parameters being a function of the internal properties, in a second step a second data set is calculated defining an image representing an estimation of the internal properties which resulted in the measured parameters, in a third step a third data set is calculated representing the parameter measurements at the perimeter of the object that would be detected if the second data set accurately represented the internal properties, in a fourth step a fourth data set is calculated representing the difference between the first and third data sets, in a fifth step a fifth data set is calculated defining an image representing an estimation of the internal properties which if present would result in parameter measurements represented by the fourth data set, in a sixth step the second and fifth data sets are combined to define a sixth data set defining a revised image representing a revised estimation of the internal properties which resulted in the measurement parameters, and in a seventh step the second data set is replaced by the sixth data set to provide a new second data set, the third to

seventh steps being repeated to produce data sets representing successively revised image representations until the difference between a calculated data set representing parameter measurements and the first data set has been reduced in a predetermined manner.

3. A method according to claim 2, wherein the third data set is normalised using data sets calculated for low and high permittivity values.

4. A method according to claim 2 or 3, wherein the third to seventh steps are repeated until an average of the difference-representing data sets is less than a predetermined value.

5. A method according to claim 4, wherein the average is a root mean square of the difference representing data sets.

6. A method according to any of claims 2 to 5, wherein the second and fifth data sets are formed using a linear back projection algorithm.

7. A method according to claim 6, wherein data formed using the linear back projection algorithm is limited to thresholds corresponding to maximum and minimum values of the measured parameters.

8. A method according to any preceding claim, wherein the data sets representing data set differences are modified by a controller prior to the subsequent image defining data set calculation, the controller acting to minimise the number of iterations required to reduce the average of the difference-representing data sets to a predetermined value.

9. A method according to claim 8, wherein the controller acts to prevent the average of the difference-representing data sets from diverging away from a predetermined value.

10. A method according to any of claims 2 to 9, wherein elements of the sixth set are modified to fall within predetermined limits, and a set of permittivity values are calculated from the modified sixth data set.

11. A method according to any preceding claim, wherein the electrical parameters measured at the perimeter of the region are voltages which are determined by capacitances defined between an array of electrodes positioned around the region.

12. A method according to claim 11, wherein the region is defined by the interior of a conduit surrounding a mixture of two or more materials of differing permittivities.

13. An apparatus for creating an image representing internal properties of a region from measurements of electrical parameters measured at the perimeter of the region, comprising means for calculating initial image data from the measurements to represent an initial estimation of the properties of the region, means for calculating estimated parameter measurement data representing the measurements which would be expected if the initial estimation of the properties was accurate, means for calculating the difference between the parameter measurements and the estimated parameter measurement data, means for calculating image correction data from the calculated difference data as if the calculated difference data had been measured at the perimeter of the region, means for combining the initial image data with the image correction data to define interim image data, and means for substituting the interim image data for the initial image data for further processing.

14. A method for creating an image, substantially as hereinbefore described with reference to the accompanying drawings.

15. An apparatus for creating an image, substantially as hereinbefore described with reference to the accompanying drawings.

The Patent Office

18

Application No:	GB 9819190.1	**Examiner:**	A J Oldershaw
Claims searched:	1 to 15	**Date of search:**	13 January 1999

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.Q): G1N NCCA, NCCE, NCCJ, NCCX, NCVX

Int Cl (Ed.6): G01F; G01N

Other: Online: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	GB2223850A (UMIST)	
A	GB2214640A (UMIST)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.